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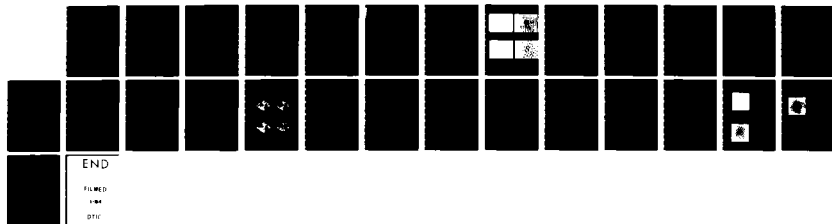
QUANTIFICATION OF INTERFERENCE AND DETECTABILITY
PROPERTIES OF VISUAL STIMULI (U) HARVARD UNIV CAMBRIDGE MA
DIV OF APPLIED SCIENCES R KRONAUER 19 MAY 83
AFOSR-TR-83-1015 F49620-81-K-0016

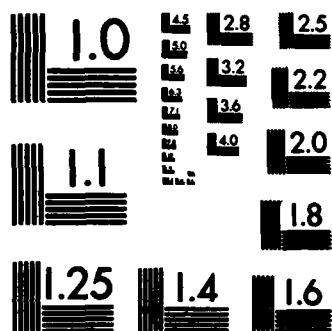
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <i>Our</i> objective is the quantitative characterization of visual spatio- temporal <i>in</i> channeling of information. The immediate approach of this study is to measure the detectability of a visual test stimulus which is a moving sinusoidal grating pattern, in the presence of a masking visual stimulus, which can be represented in spatio-temporal frequency space as band-limited two- dimensional dynamic visual noise. <i>We have</i> performed coherent masking studies in which the mask is a high-contrast traveling wave grating and have discovered <i>He has</i> cont'd		

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at the masking function is very asymmetrical in spatial frequency when the mask and test gratings are matched in velocity. We have also discovered that limited two-dimensional visual noise can be simulated by discrete (uncorrelated) spectral components lying within the desired band and that as few as six components can give a representation indistinguishable from continuous-spectrum noise. To perform these band-limited visual noise studies we have created a unique computer-controlled system for image generation.

↑ this is for

F49620-81-K-0016
Annual Report
19 May 1983

QUANTIFICATION OF INTERFERENCE AND
DETECTABILITY PROPERTIES OF VISUAL STIMULI FOR OPTIMAL
DISPLAY DESIGN

Harvard University
Division of Applied Sciences
Cambridge, MA 02138

Dr. Richard Kronauer

Controlling Office: USAF Office of Scientific Research/ML
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2. Research Program Objectives

In the design of visual displays it is important that different types of information be presented free of interference with each other. It is well known that one visual stimulus can mask the detection of another if they are similar in spatial and temporal characteristics. Such interference diminishes with increasing stimulus difference, and interference below some acceptably low level can be used as a design criterion.

Continuous information transfer requires a varying, unpredictable stimulus. To assess the masking properties of an information-containing visual field it is necessary that the mask be in some sense random. We have interpreted the limited existing data on random (noise) masking as implying a greater potency to the finite bandwidth random mask than to the nonrandom (single-component) grating.

Both the test and mask stimuli are characterized in a 3-dimensional spatio-temporal frequency space. The test stimulus is in all instances a traveling-wave sinusoidal grating (i.e., has a single punctate representation in frequency space, together with the necessary conjugate point). The mask stimulus is either coherent (i.e., a single, traveling sinusoidal wave) or incoherent (i.e., occupies a finite 3-dimensional band volume in frequency space). Since 3 parameters are required to specify the test stimulus, while 9 parameters are required for the incoherent mask (3 reference frequencies for the centroid of the mask spectral power and 6 second moments of spectral power with respect to the centroid), a complete study would involve a total of 12 parameters. To address the overwhelming complexity of a 12 parameter study we resort to "cuts" of reduced dimensionality. For example, the use of a coherent mask reduces the dimensionality from 12 to 6. However an essential objective of the research is the characterization of the anticipated major increase of masking efficacy when the mask is incoherent rather than coherent. Therefore the results of the coherent mask studies are used to choose the most relevant combination of parameters for the incoherent masking experiments.

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3. Status of the Research

3.1 Coherent Masking Studies

Underlying our original Proposal was the concept that masking bands would generally be symmetrical, with respect to spatial and temporal frequencies, centered on the masking wave vector (Proposal Appendix C), and that the major interest would be the bandwidths of masking for various "cuts" through three-dimensional spatio-temporal frequency space. We began with knowledge of one 2D "cut" in 3D space (namely for $f_t = 0$, so all components were stationary), and next explored another "cut" (namely $\theta = 0$, so all components shared the same orientation). Due to delays in delivery of our own equipment we began these studies with borrowed facilities (M.I.T. Manned Vehicle Laboratory), using a simpler psychophysical procedure which was a modified method of adjustment. Our first spatio-temporal "cut" in 3D space, using travelling-wave mask and test components, revealed extreme asymmetry of masking, the mask (4 c/deg, 8 Hz) very strongly masked patterns of lower spatial and temporal frequency, while facilitating the detection of higher spatial frequency test patterns. (See 1982 Informal Progress Report, Appendix A.) We also discovered that the strongest masking effects occur when the mask and test components are matched in velocity, so that they both have the same ratio of temporal to spatial frequencies.

In brief, we have found that the addition of sustained, travelling-wave motion profoundly affects the entire masking phenomenon. It is important that these results be precisely documented for publication. We have been able to confirm these results using signal detection theory with forced-choice "staircases", and we are currently exploring in further detail the full extent of the facilitation regime. We anticipate conclusion of this particular phase of work by the end of this contract year. The completion of these coherent masking studies will entail exploring the full 3D masking function, in the same travelling-wave paradigm, in order to characterize the band-volumes of sensitivity reduction and enhancement in spatio-temporal frequency space.

3.2 Finite Bandwidth Noise Masking

As outlined in the Proposal, we are approximating continuous band-limited two-dimensional noise images by ensembles of discrete points in the spatial frequency domain (punctate 2D spectra), due to data rate limitations in computer controlled displays of reasonable cost. We have developed a powerful and flexible system of hardware and software which synthesizes dynamic two-dimensional visual patterns from such ensembles of Fourier components, defined in a three-dimensional spatio-temporal frequency space such that each combination of spatial frequency, orientation, and temporal frequency has an associated amplitude and phase. At our current

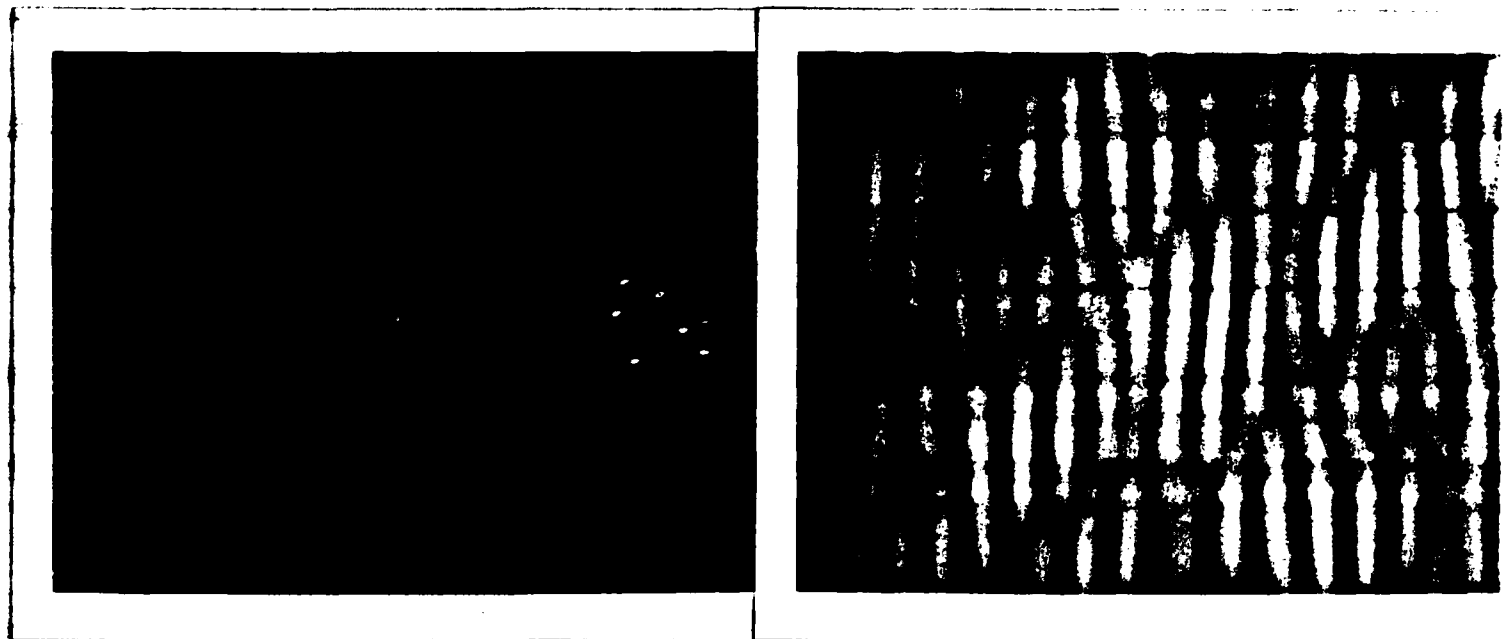
image generation frame rate of 250 frames/second, we can synthesize spatio-temporal textures containing as many as 20 such Fourier components when two components of matching orientation are presented in each frame. Further details concerning these developments may be found in Appendix C.

With the computer and display hardware in place our first objective was to determine how few punctate spectral components were required to simulate dynamic bandlimited 2D noise. We conjectured in the Proposal that as few as 16 might suffice, and we were prepared to find that perhaps as many as 50 would be required. We were amazed to discover that the true minimum could be as few as 6, if they were suitably chosen within relatively narrow bandwidths (of about one octave of spatial frequency and 30° of orientation). As the bandwidth of the 2D noise to be simulated increases, the required number of components increases, and the principle appears to be governed by the psychophysical 2D masking bandwidth based on a single Fourier component (the putative 2D channel band area). Thus, as long as the punctate spectral components lie within the coherent masking bands of one another, and as long as the number of discrete Fourier components is 6 or more, their sum will be approximately indistinguishable from continuous, stationary bandlimited 2D spatial noise. This point is illustrated for both isotropic and anisotropic spectra in Figure 1. It appears that even fewer components may be required for simulating dynamic 2D noise, since the different temporal frequencies associated with each Fourier component remove coherence of the image across time. Since these effects can only be appreciated in a dynamic visual display, we have prepared a videotape and an accompanying descriptive brochure which has been submitted to the contract monitor. The final section of the videotape presents an isotropic spatio-temporal texture synthesized from the same 10 components (but with temporal frequency included) as used in the isotropic texture shown in Figure 1b. The dynamic isotropic texture appears even more incoherent than the static one, even though both have the same punctate spatial spectrum.

A basic premise of our original Proposal was that finite band noise masking was more effective than very narrow band or coherent masking. Our basic experiments have already confirmed this. For example, if a Subject cannot distinguish between patterns composed of 5 punctate components vs. 6, it means that the sixth component is effectively 'masked' by the other 5. Since all components have the same contrast, C , the 5 component texture has an overall (expected peak-to-peak) contrast of $C\sqrt{5}$ which means that any single component is undetectable in a mask whose contrast is only $\sqrt{5}$ larger. This is far more effective than coherent masking.

The 1983 Informal Progress Report (Appendix B here) describes how the band-limited stimulus gives the percept of modulation "net" overlying a carrier wave, and discusses the implications of this percept for

a.



b.

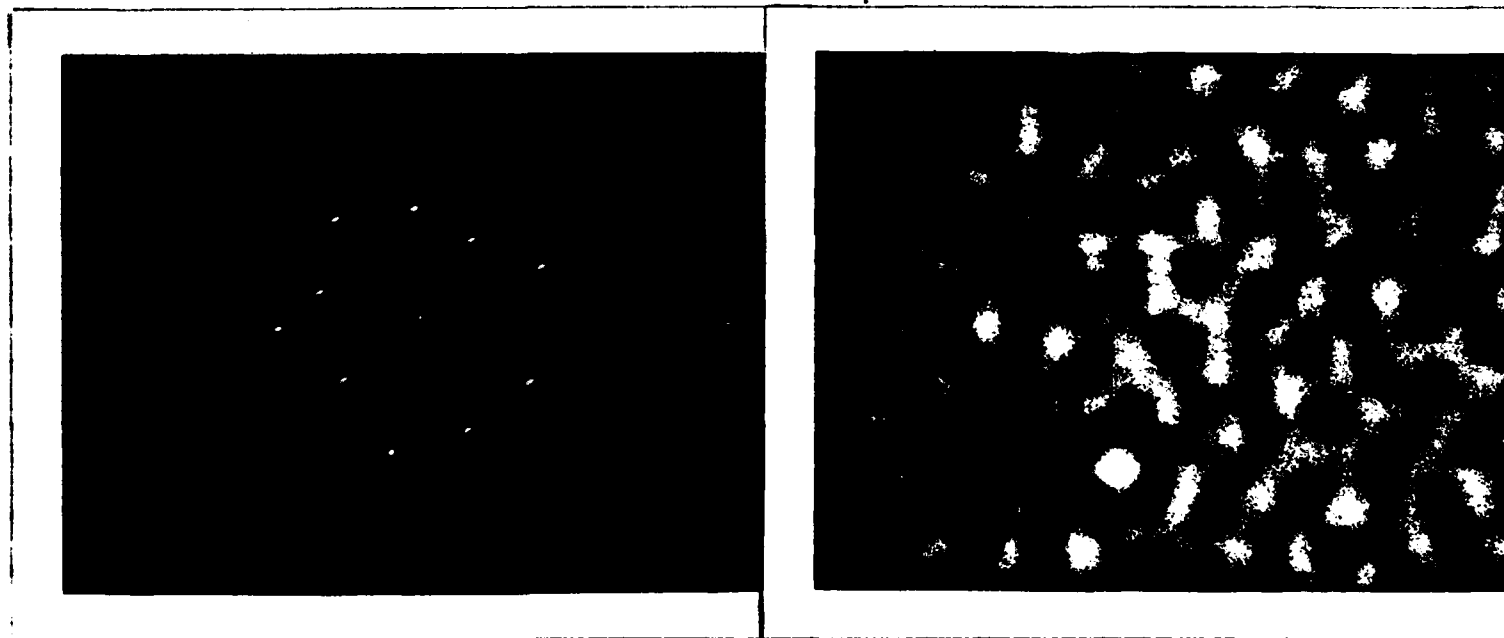


FIGURE 1 Example of (a) a six-component anisotropic noise pattern, and
(b) a 10-component isotropic noise pattern, with punctate 2D
spectra as indicated in the Fourier plane (left Panel each Figure)

identifying essential underlying nonlinearities in visual system processing. When the band-limited stimulus is composed of travelling-wave components the variety of percepts is remarkable. For example, the modulation net and the carrier can have completely different perceived directions of motion, leading to a bi-stable motion percept. This is documented in the videotape mentioned above which was presented at the 1983 ARVO meeting and in an expanded form will be shown at the 6th European Conference on Visual Perception. This videotape together with its supporting descriptive brochure, constitutes an essential part of this Progress Report.

4. Publications

Daugman, J.G. (1982). Uncertainty relation for resolution in space, spatial frequency, and orientation optimized by two-dimensional visual cortical filters. Journal of the Optical Society of America, accepted pending revisions.

Daugman, J.G. (1983). Six formal properties of two-dimensional anisotropic visual filters: Structural principles and frequency/orientation selectivity. IEEE Transactions on Systems, Man, and Cybernetics. (In Press).

Daugman, J.G. (1983). Is visual orientation selectivity independent of retinal eccentricity? A theoretical note. Perception, accepted pending revisions.

Zeevi, Y.Y. and Kronauer R.E. (1983). Reorganization and diversification of signals in vision. (Submitted to IEEE).

Daugman, J.G. (1983). Spatial visual channels in the Fourier plane. Submitted, Vision Research.

5. Professional Personnel: (4/1/82 - 3/30/83)

Richard E. Kronauer, Gordon McKay Professor of Mechanical Engineering	Principal Investigator
Yehoshua Y. Zeevi, Professor of Electrical Engineering, Technion Haifa, Israel	Associate Investigator
Charles F. Stromeyer III, Research Associate in Biomedical Physics Harvard University	Associate Investigator
John G. Daugman, Ph.D. Awarded June 1983 Thesis title, "Spatial Visual Channels in the Fourier Plane"	Associate Investigator
Benjamin Dawson, Ph.D., Massachusetts Institute of Technology	Consultant
Judith A. McArthur	Research Assistant

6. Interactions

Daugman, J. G. (1981). Spatial channels in the two-dimensional Fourier plane. Fourth European Conference on Visual Perception. Paris, September, 1981.

Zeevi, Y.Y., Kronauer, R.E. and Daugman, J.G. (1982). Spatio-temporal masking: Asymmetry, nonseparability, and facilitation. ARVO, Sarasota, Florida, May 1982.

Daugman, J.G. (1982). Polar spectral nonseparability of two-dimensional spatial frequency channels. ARVO, Sarasota, Florida, May 1982.

Daugman, J.G. (1982). Uncertainty relation for resolution in orientation, spatial frequency, and space optimized by two-dimensional visual filters. Fifth European Conference on Visual Perception. Leuven, Belgium; Sept. 1982. Abstract published in Perception, Vol. 11, pp. A16-A17, 1982.

Daugman, J.G., Kronauer, R.E., and Zeevi, Y.Y. (1982). Perceived randomness in images with sparse punctate two-dimensional spectra. Fifth European Conference on Visual Perception. Leuven, Belgium; September, 1982. Abstract published in Perception, Vol. 11, p. A22, 1982.

Zeevi, Y.Y. and Kronauer, R.E. (1982). Reorganization and diversification of signals in vision. Presented at the 35th ACEMB/IEEE Meeting, Philadelphia. Pa.

Daugman, J.G. (1982). Uncertainty relation for orientation, spatial frequency, and space optimized by two-dimensional visual filters. Annual Meeting of the Optical Society of America, Tucson, Oct. 1982. Abstract published in Journal of the Optical Society, Vol. 72, p. 1785 (1982).

Kronauer, R.E., Zeevi, Y.Y. and Daugman, J.G. (1982). Degree of disorder perceived in images with punctate spectra. Annual Meeting of the Optical Society of America, Tucson, Oct. 1982. Abstract published in Journal of the Optical Society, Vol. 72, p. 1798 (1982).

Daugman, J.G. (1983). Efficiency of visual mechanisms in the two-dimensional spatial and Fourier planes. Troisieme Seminaire Hivernal Des Neurosciences Europeennes. Les Arcs (Savoie), France, March 1983.

7. Inventions and Patents. None

8. Appendices

8.1 Appendix A -- Informal Scientific Report, March 1, 1982 (attached)

8.2 Appendix B -- Informal Scientific Report, March, 1983 (attached).

8.3 Appendix C -- Technical Developments (attached).

QUANTIFICATION OF INTERFERENCE AND DETECTABILITY PROPERTIES OF
VISUAL STIMULI FOR OPTIMAL DISPLAY DESIGN

Contract No. F49620-81-K-0016

Progress Report: June 30, 1981--Mar. 1, 1982

Submitted to:

Dr. G.M. Haddad
Program Manger
Life Sciences Directorate
Dept. of the Air Force
Air Force Office of Scientific
Research
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Submitted by:

Professor Richard E. Kronauer
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Cambridge, Massachusetts 02138

Background

Since this is an initial report covering only 8 months of activity it is appropriate to review briefly the objectives of the three-year study. Simply stated we intend to measure the detectability of a sinusoidal traveling-wave grating in the presence of a mask of band-limited spatiotemporal noise. The mask is specified in terms of three spectral variables: temporal frequency, f_t , and two spatial frequencies, f_x and f_y . Alternatively, the two spatial frequencies can be replaced by a single spatial frequency, and a wave orientation, f_s and θ , where $f_x = f_s \cos \theta$ and $f_y = f_s \sin \theta$. A total of six quantities are required to specify the mask: three quantities defining the spectral center of the noise band and three bandwidths.

Some rather limited existing data have suggested that a noise mask which is temporally broad-band is considerably more effective at a given contrast level than is a temporally coherent mask. Our aim is to study this question in the general context of the full three spectral dimensions and to ascertain for which bandwidths the masking property makes the transition from the less effective "coherent" state to the more effective "random" state.

The generation of band-limited noise masks in real time is a technically challenging one. The method we are developing consists of storing, in a computer, sequences of temporally correlated numbers which represent the amplitudes of discrete spatial frequency components (i.e., individual sine wave gratings). These sine wave gratings are generated on a CRT by preprogrammed electronics and a large number can be combined by frame interleaving. To avoid the contrast degradation resulting from many interleaved frames we are electronically summing gratings of matched orientation before generating the CRT representation.

Hardware Development

The experimental apparatus consists of the controlling digital computer, the special purpose electronics for grating generation and the display unit. We have acquired a PDP 11-34 computer which is installed

and running with an RT-11 operating system. It happened that the funds requested in our research proposal (and allocated) were insufficient to purchase a new computer with essential peripherals at current prices. Consequently we purchased a used computer and are pleased to find that it performs excellently. In order to effect a long range economy we requested permission to expend first-year funds for an in-lab graphics capability so that data evaluation and presentation could be done efficiently and cheaply. This equipment is now in place.

We have had a temporary bottleneck in the construction of the specialized electronics. Almost all of the components are now on hand and we expect to do prototype testing in 6 to 8 weeks. The display unit, a Tektronix 608, is in place.

Preliminary Studies

There are two directions in which we have been able to proceed before the availability of the computer generated noise mask. The first is to extend the study of coherent masking to three spectral dimensions. Since the coherent mask represents the limit of zero-bandwidth random masking it is a situation which must necessarily be understood as a reference for all finite bandwidth studies. The second direction is to make estimates of how many discrete components will be required within any finite three-dimensional spectral band to give the appearance of randomness. This will serve as a guide to the adequacy of our electronics hardware package.

Coherent Masking Results

In our studies we have elected to hold f_x , f_y , and f_t of the mask fixed and vary f_x , f_y , and f_t of the test grating. A relatively simple transformation can convert these results to the inverse case if desired. Rather than plunge into the full 3-dimensional variation of the test

f_x , f_y and f_t we have elected to take 2-dimensional cuts in the 3-space. The first such cut is to make f_t of the test match that of the mask and vary only f_x and f_y . The study of the special sub-case where both the mask and test have $f_t = 0$ (i.e., the mask and test are stationary and the test is turned on and off slowly) was begun before this research contract by one of us (J.G. Daugman) and has been brought to completion during this reporting period. The key results are summarized in an abstract prepared for the 1982 ARVO meeting together with a set of data figures (both attached). These results show to be fallacious the commonly preconceived view that such a 2-dimensional masking function should be polar separable (i.e., the product of a function solely of spatial frequency with a function solely of orientation). Moreover they show that the masking bandwidth for gratings which are colinear is about twice as broad as for gratings which have the same frequency but differ in orientation.

The second 2-dimensional cut in 3-space we have studied is to make the orientation of the test match the mask and vary only f_s and f_t (i.e., the mask and test are colinear waves traveling in the same direction but with different f_s and f_t). We have made extensive studies with three subjects. The results, summarized in another abstract for ARVO, are attached, along with a contour plot of the masking function. When the mask and test match in f_t the masking is reasonably symmetric in f_s (as we had anticipated), but when they match in f_s the masking is very asymmetrical in f_t . What is especially surprising is that when the mask and test match in drift velocity there is a very great asymmetry (actual facilitation for test frequencies higher than the mask). One fact is clear: the subjects did not follow the traveling-wave mask with smooth eye movement, for had they done so the detection of the matched-velocity test would have given a much more symmetrical masking function. We are in the process of thinking through the implications of these unusual findings for our projected random mask studies.

Achieving Randomness with Few Spectral Components

Previous work has suggested that four colinear gratings with irrational frequencies can give a good impression of randomness. Our preliminary studies confirm this but go beyond it. We have found that for only two components, with frequencies in the ratio of 1.61, it is difficult for the observer to be specific about the nature of the intrinsic regularity. There appear to be selected frequency ratios, 1.61 and others, which convey the impression of maximum irregularity and we plan to document this more precisely. However, two gratings with different orientations always give an identifiable regular pattern regardless of their spatial frequencies. The reason is that where two orientations are concerned what the brain perceives is the difference of the two wavevectors (i.e. the low spatial frequency modulation present in the combined pattern). Thus, two components reduce to one net percept. We are now testing whether three grating components, so oriented that the difference wavevectors are related in some optimal irrational way, might give an appearance of irregularity analogous to the case of two colinear gratings. For the present all we can say is that the appearance of randomness in orientation is less easy to achieve than in spatial frequency. The implication for the generation of band limited noise masks is that we may have to use the full complement of 10 orientations originally planned.

Professional Personnel

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**POLAR SPECTRAL NONSEPARABILITY OF TWO-DIMENSIONAL SPATIAL
FREQUENCY CHANNELS.** John G. Daugman, Harvard University.

Spatial frequency channels are usually conceptualized as the product of a spatial frequency tuning curve times an orientation tuning curve. This implicit assumption of polar spectral separability was examined by 2AFC masking experiments in which the superimposed mask and test gratings spanned the 2D Fourier plane (i.e. all relative orientations and spatial frequencies). A 2D channel tuning surface was thus constructed over the Fourier plane, interpolated from a Cartesian grid of 121 sampling points, for each of four subjects.

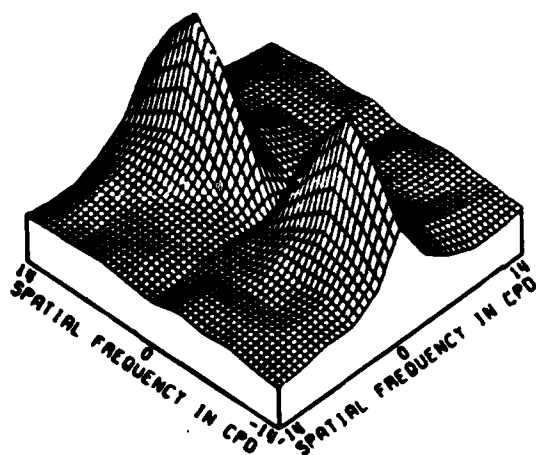
These channel tuning surfaces have iso-sensitivity contours which are roughly elliptical, but they are neither Cartesian nor polar separable. The orientation bandwidth of a single channel changes dramatically depending on the probe spatial frequency relative to the channel's preferred frequency. For all four subjects there was a monotonically decreasing relationship between orientation bandwidth and probe spatial frequency, ranging from an orientation half-width of 32 degrees when probing 1.5 octaves below the channel's preferred frequency to a half-width of 6 degrees when probing one octave above. Thus a spatial visual channel is manifestly not expressible as the product of a spatial frequency tuning curve times an orientation tuning curve.

Inverse 2D Fourier transformation of the data reveal the underlying even and odd space-domain kernels (point-spread functions) of the 2D channels, which resemble classic elongated center-surround receptive fields. These characteristics of anisotropic localized visual filters are analyzed in terms of 2D Gabor theory of joint uncertainty minimization. (Supported by AFOSR Contract # F49620-81-K-0016).

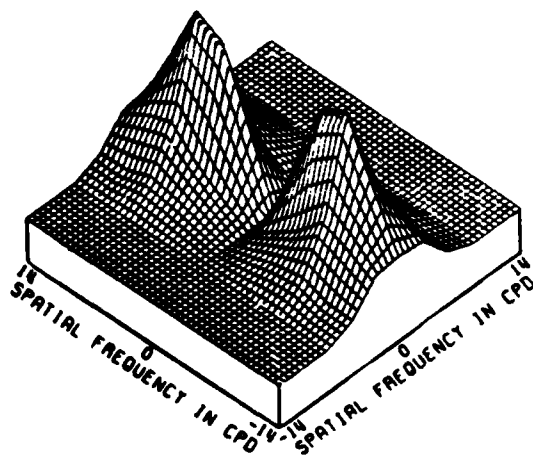
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CHANNEL TUNING SURFACE OVER THE FOURIER PLANE

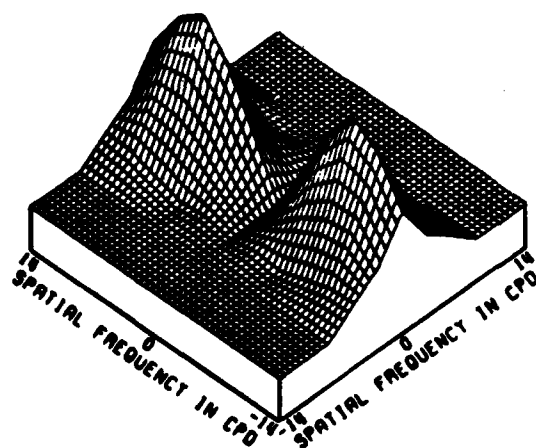
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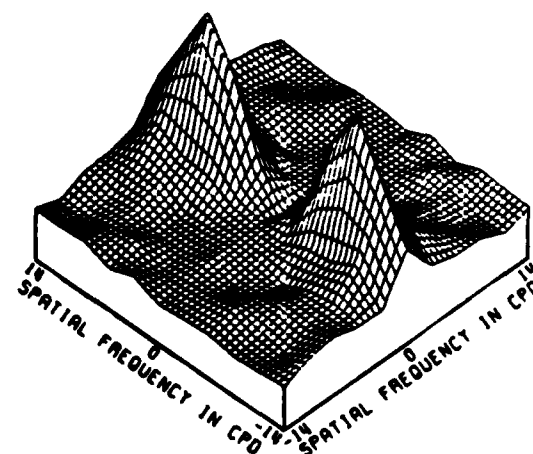
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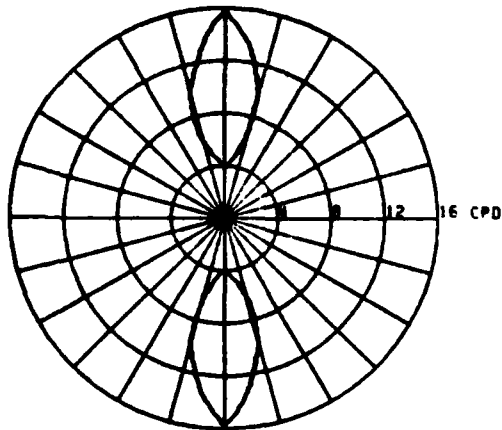


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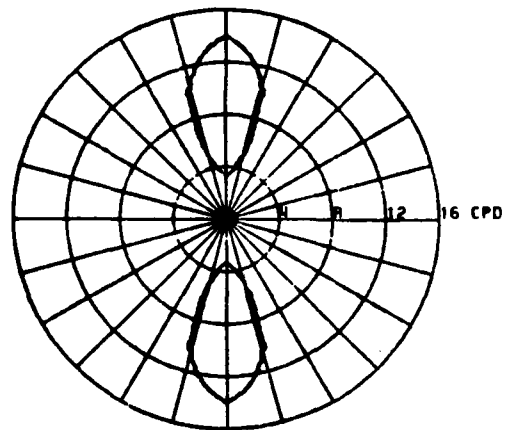


-3 DB CHANNEL LOCI IN FOURIER PLANE

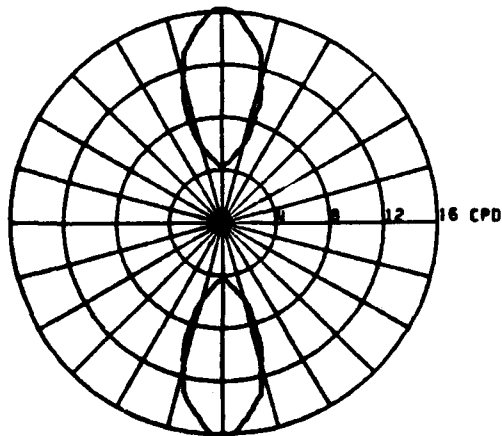
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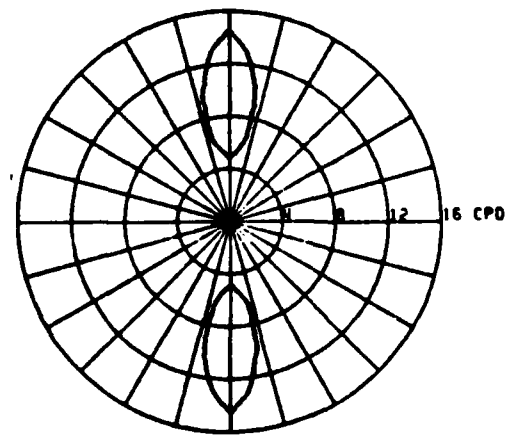
SUBJECT JD



SUBJECT WC



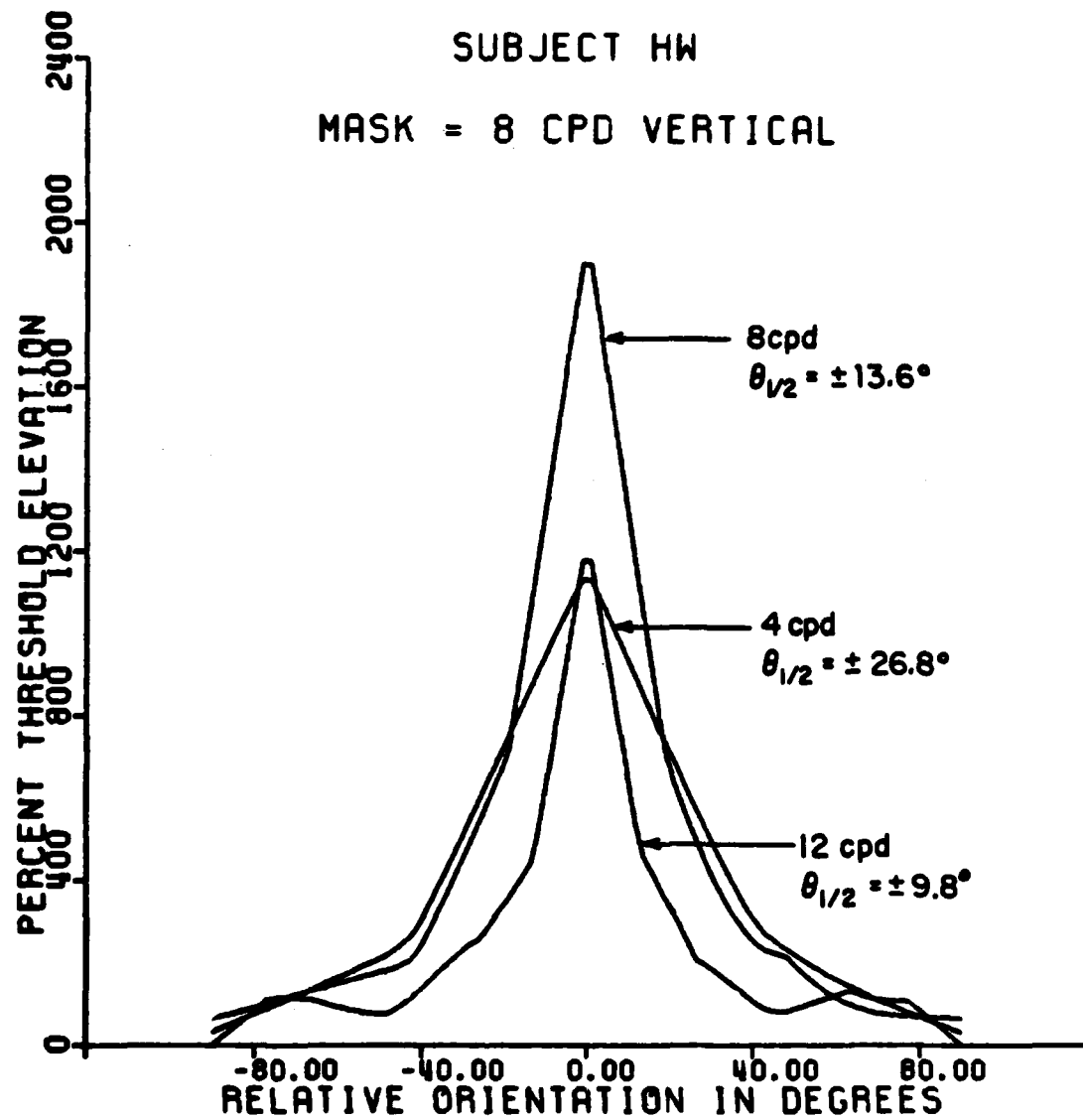
SUBJECT RF



ANGULAR CROSS-SECTIONS OF CHANNEL TUNING SURFACE

SUBJECT HW

MASK = 8 CPD VERTICAL



NAME

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INITIALS, FIRST NAME, AND
PRESENTING MATERIAL

ZEEVI

(617) 495-2850

Type TITLE, Author(s), Affiliation and Abstract within the borders of the box below

SPATIOTEMPORAL MASKING: ASYMMETRY, NONSEPARABILITY AND FACILITATION. Y.Y. Zeevi, R.E. Kronauer, J.D. Daugman.
Division of Applied Sciences, Harvard University.

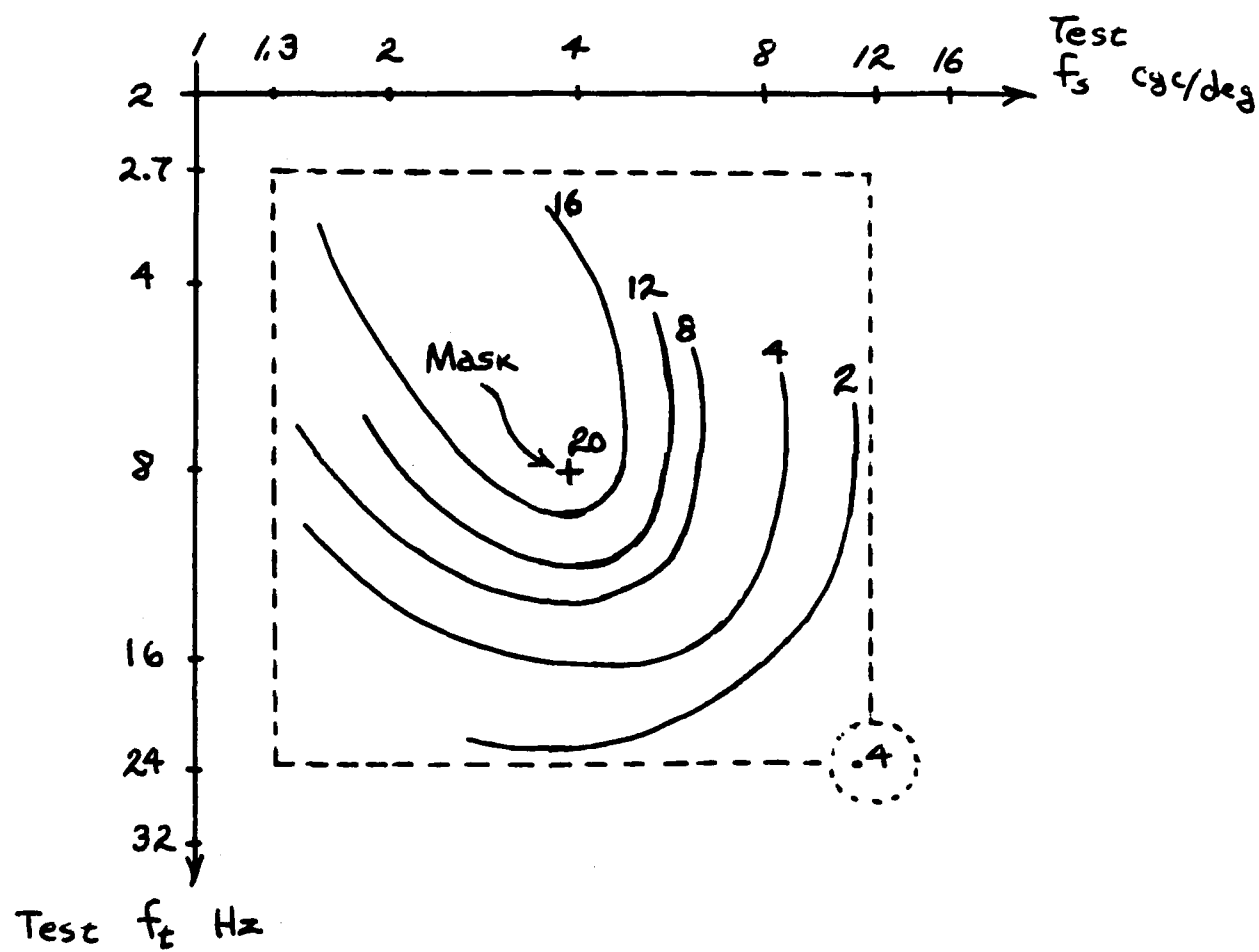
We have studied masking between sinusoidal gratings, drifting codirectionally, which may differ in both drift frequency, f_t , and spatial frequency, f_s . The mask is ever-present. The test grating pulse is 250 msec (cosined envelope) preceded by a warning tone. Contrast threshold, C_{th} is measured by a modified staircase procedure. Masking effectiveness, m , is the ratio of C_{th} with mask to C_{th} without mask.

A 40% contrast mask with $f_s = 4$ cpd and $f_t = 8$ hz gives, for a test with matching f_t, f_s presented in phase, $m=20$. For test gratings which match the mask in f_t the masking effectiveness is symmetric in f_s (on a linear plot) with $m=10$ found at about 2 cpd and 6 cpd. For test gratings which match the mask in f_s , ($f_s=4$ cpd) m is very asymmetric; m drops sharply for $f_t > 8$ hz ($m=10$ at $f_t=12$ hz) but is sustained for $f_t < 8$ hz ($m=14$ at $f_t=2.66$ hz). For test gratings which match the mask drift velocity (and presented in cosine phase when harmonically related) the masking asymmetry is even stronger. The detection of 3rd harmonic test gratings ($f_s=12$ cpd, $f_t=24$ hz) is strongly facilitated ($m<.3$) while the detection of 1/3 subharmonic ($f_s=1.33$ cpd, $f_t=2.66$ hz) is strongly masked ($m=14$).

Thus, the spatiotemporal masking surface $m(f_s, f_t)$ is not separable into a product of functions of f_s and f_t alone.

(Supported by AFOSR contract F49620-81-K-0016.)

XX



MASKING FACTORS FOR COLINEAR TRAVELING WAVES

March, 1983

INFORMAL SCIENTIFIC REPORT

Contract No. F49620-81-K-0016 "Quantification of Interference and Detectability Properties of Stimuli for Optimal Display Design."

Our research is directed toward quantifying the masking effects of stochastic spatio-temporal images. Since there are very many parameters in such a study we began with a preliminary exploration of the simplest spatio-temporal masking paradigm: The ability of simple traveling-wave sinusoidal grating to mask another simple traveling-wave grating of similar orientation. The spatial and temporal frequencies of the mask and the test gratings are the parameters of the study. Our results (1) show that the masking function is symmetrically band-limited in the relative velocities of the two gratings. However, at any fixed velocity the masking function is strongly asymmetrical in spatial frequency: masking is strongly sustained toward lower frequencies while at high frequencies masking declines rapidly and actually becomes replaced by facilitation. These unexpected results corroborate, in a qualitative sense, the electrophysiological findings of DeValois and Tootell, on cat cortical "simple" cells (2).

As part of the more ambitious plan to study the masking properties of spatio-temporal, spectrally 3D band-limited visual noise we have addressed the technical problem of generating and controlling such patterns in real-time. To produce these dynamic visual images on a C.R.T. within the data rate limitations of a modest computer we are approximating continuous spectra by discrete (punctate) components within the desired 3D spectral band of spatial and temporal frequency and orientation. The basic technical questions are how many such components are required to make a perceptually adequate approximation to the continuous 3D spectrum and how should they be distributed.

These technical questions have opened an unanticipated and rich line of inquiry into visual system function. The issues are both fundamental and subtle. We approached the study first with combinations of discrete,

stationary spectral components (i.e., the temporal frequency, f_t , is zero) and were surprised to find that as few as 6 such components give the appearance of filtered 2D white noise if the components are properly chosen within the pass-band of spatial frequency and orientation. We have worked out tentative rules for choosing these components (e.g. avoiding repetition of wave vector orientation or spatial frequency, and avoiding clustering). The accompanying figures show the appearances of images composed of 4, 6, and 8 components to demonstrate the remarkable efficacy of small numbers of components to simulate a 2D spatial stochastic process. We have adopted the criterion that N components are adequately representative of the continuous spectrum when an observer can reliably see no difference between images containing N and N+1 components.

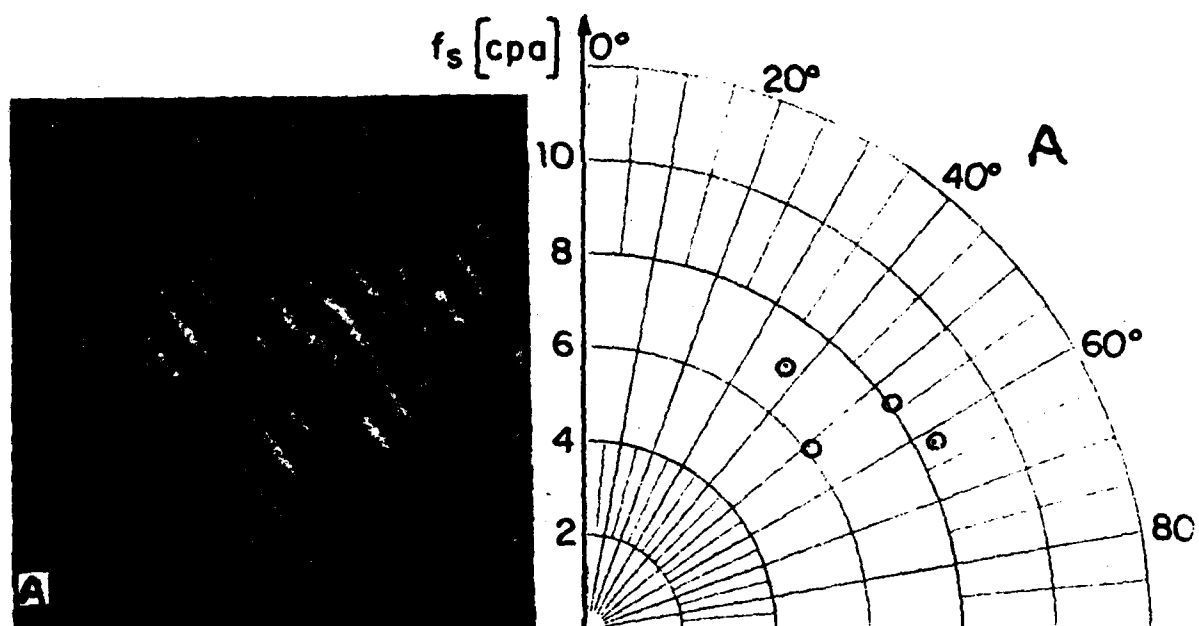
Most striking is the percept which these band-limited images provide: that of a "carrier" wave component (representing the centroid of the N components in the 2D spatial Fourier plane, i.e., an average spatial frequency and orientation) modulated by an overlying "net" (representing changes of contrast and phase). The overlying net of 2D amplitude and phase modulation (2DAPM) has local dimensions determined by the difference frequency vectors, i.e., the "beats" among the spectral components. If temporal frequency is added to each discrete 2D spatial frequency component the percept becomes even more fascinating, in a way which is impossible to appreciate without observation. Depending on how the temporal frequencies are assigned, the "carrier" and modulation "net" may have completely different apparent directions of motion, enhancing their discriminability and making it easy to switch attention between them. If anything, the "net", which contains apparent spatial frequencies far removed from those actually present in the image, is the dominant percept.

The fact that beat frequencies (i.e., frequency difference-vectors) are so strongly and dominantly perceived suggests strong nonlinearities in the visual system. The experimental paradigm in which a small number of discrete spectral components are combined permits a unique quantitative approach to the study of these nonlinear effects (4). We have already been able to show that the very simple beat pattern between two components constitutes a moderately effective

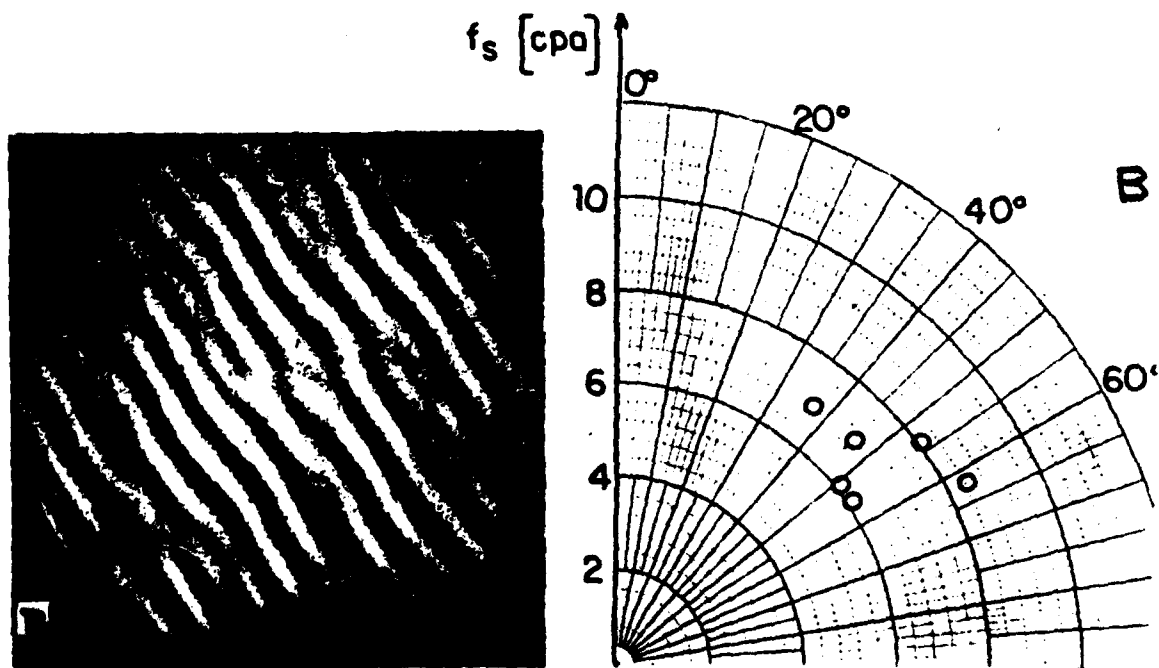
mask of that non-existent spectral frequency. We plan to extend these studies to the more complex beat pattern of N components (the 2D "net") and in particular we intend to explore whether 2D phase modulations are, by themselves, less effective in masking than are contrast modulations. Nachmias and Rogowitz (3) have carefully studied the very simple case of vertical stationary gratings and find that phase modulations are somewhat less effective. The modulation percept is so markedly different when two space dimensions and time are involved that it would be impossible to extrapolate these findings to it.

In summary, our original plan to study the masking effects of band-limited visual noise on spectral components within or near the 3D band-volume in question has now been expanded to consider effects on certain spectral components far removed from the band. These extended results promise to be very significant in quantifying the nonlinear performance of the human visual system. Indeed, the combination of the traditional spatio-temporal characterization of the visual system (generalized to three dimensions), and our new description in terms of the response to combinations of 3D frequencies, are analogs of the first two kernels of the full Wiener expansion of a nonlinear system (4).

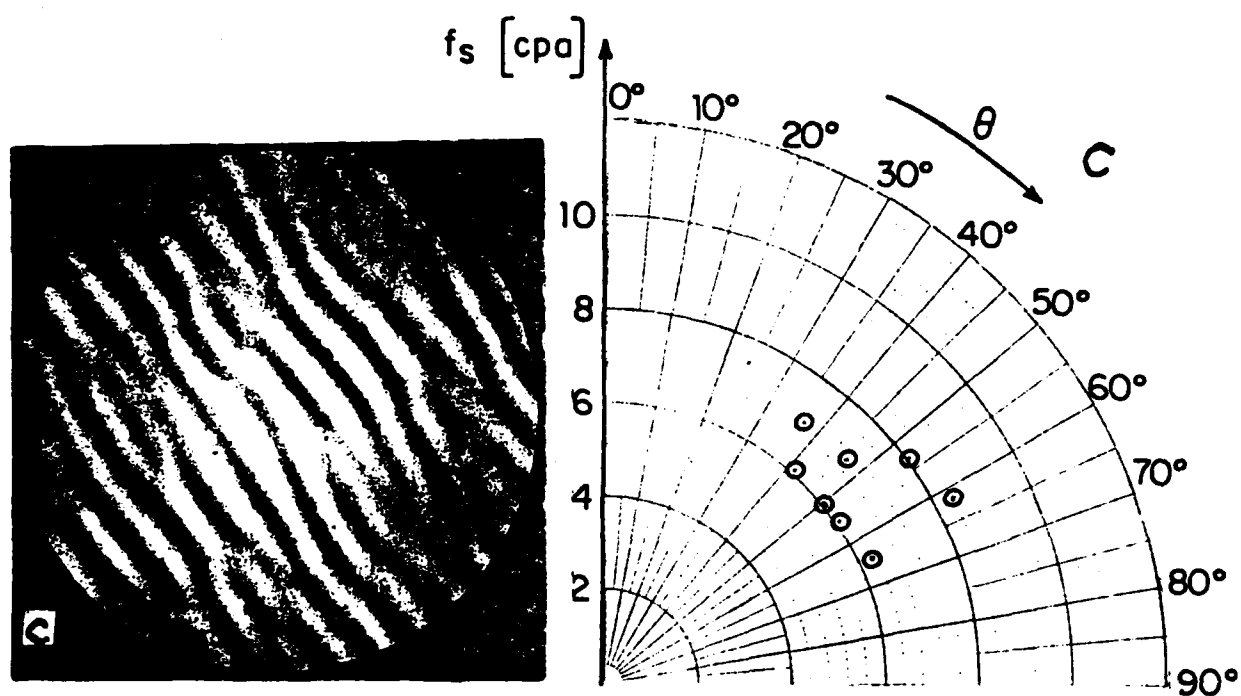
1. "Spatiotemporal Masking: Asymmetry, Nonseparability, and Facilitation," Y. Y. Zeevi, R.E. Kronauer, and J.G. Daugman, presented at the Annual Spring Meeting, The Association for Research in Vision and Ophthalmology, May 1982.
2. "Spatial Frequency Inhibition in Cat Striate Cortex Cells," K.K. DeValois and R.B.H. Tootell, presented at the Annual Spring Meeting, The Association for Research in Vision and Ophthalmology, May 1982.
3. "'Masking' by Spatially Modulated Gratings," J. Nachmias and B.E. Rogowitz, presented at the Annual Spring Meeting, The Association for Research in Vision and Ophthalmology, May 1982.
4. Nonlinear Problems in Random Theory, N. Wiener, MIT Press, Cambridge, Mass., 1958.



4 COMPONENTS



6 COMPONENTS



8 COMPONENTS

8.3 Appendix C - Technical Developments

We have developed the capability to display dynamic two-dimensional visual patterns which are synthesized in real-time from ensembles of Fourier components specified in a 3D spatio-temporal frequency space. We can synthesize textures containing as many as 20 such Fourier components, in 10 co-directional pairs, with independently specified spatial frequencies, amplitudes, phases, orientations (with a resolution of 1/3rd of a degree), and temporal frequencies. We can also limit each Fourier component to a spatial region defined by an electronic image 'window' having controllable 2D location and radius (if circular) or width and length (if rectangular).

The system is fully interactive with a PDP1134 mini-computer which commands lists of 3D Fourier components to be synthesized and displayed on a Tektronix 608 monitor. The individual parameters of such textures can be controlled manually, as well as by computer. The images are generated at a frame rate of 250 frames/second.

We have been developing a growing library of computer programs which accomplish certain spectral operations in real-time, such as transformations of a spectral cluster in the spatial Fourier plane. These include simple translation of the spectral distribution in an arbitrary direction in the frequency domain; simple rotation around the cluster's centroid; simple dilation relative to the cluster's centroid; and dilation relative to the origin of coordinates of 3D frequency space. We have made a video tape demonstrating these various spatio-temporal frequency transformations, using both coherent and incoherent spectral combinations.

Our software developments allow us to call up any particular spatio-temporal texture from disk for controlled display to a Subject, who is then interrogated in various standard psychophysical paradigms such as signal discrimination and detection.

We have integrated a second display system into the first, which permits the simultaneous display of the spectrum of the image in the Fourier plane. Thus these two displays can be interpreted as being the 2D Fourier transforms of each other, analogous to holographic representations. The attached Figure gives two examples of such 2D signals represented in both domains. As the spatial 2D spectrum of a texture evolves in time, we see simultaneously the space-domain image and the equivalent spectral representation. Our dual display system has the same power and advantages as seeing a voice spectrogram evolving in time simultaneously with spoken speech.

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